Neutrino Oscillations as Probes of GUTs
(and fundamental physics in general)

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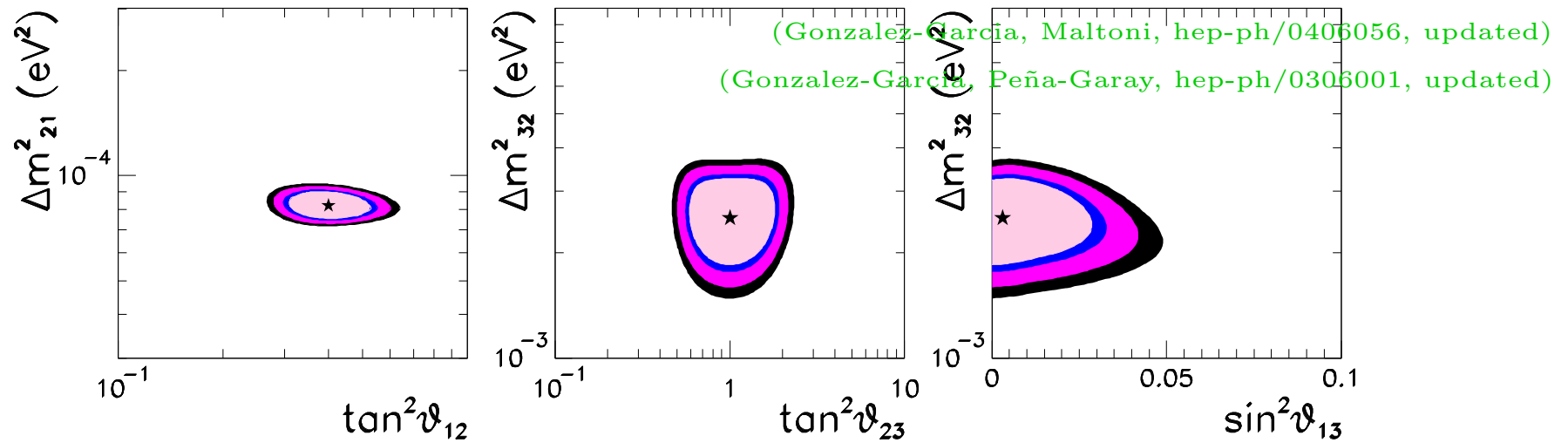
Neutrino Oscillations Working Group (WG1),

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Outline

1. What We Learned, What We Still Need to Find Out (BRIEF);

2. Neutrino Masses Are Small;

3. Understanding Fermionic Mixing: Quark versus Lepton Mixing;

4. Comments on Leptogenesis;

5. Concluding remarks;

1. All (?) Neutrino Oscillation Data Fit By Three-Flavor Oscillations

(Gonzalez-Garcia, Maltoni, hep-ph/0406056, updated)

(Gonzalez-Garcia, Peña-Garay, hep-ph/0306001, updated)

$$
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}
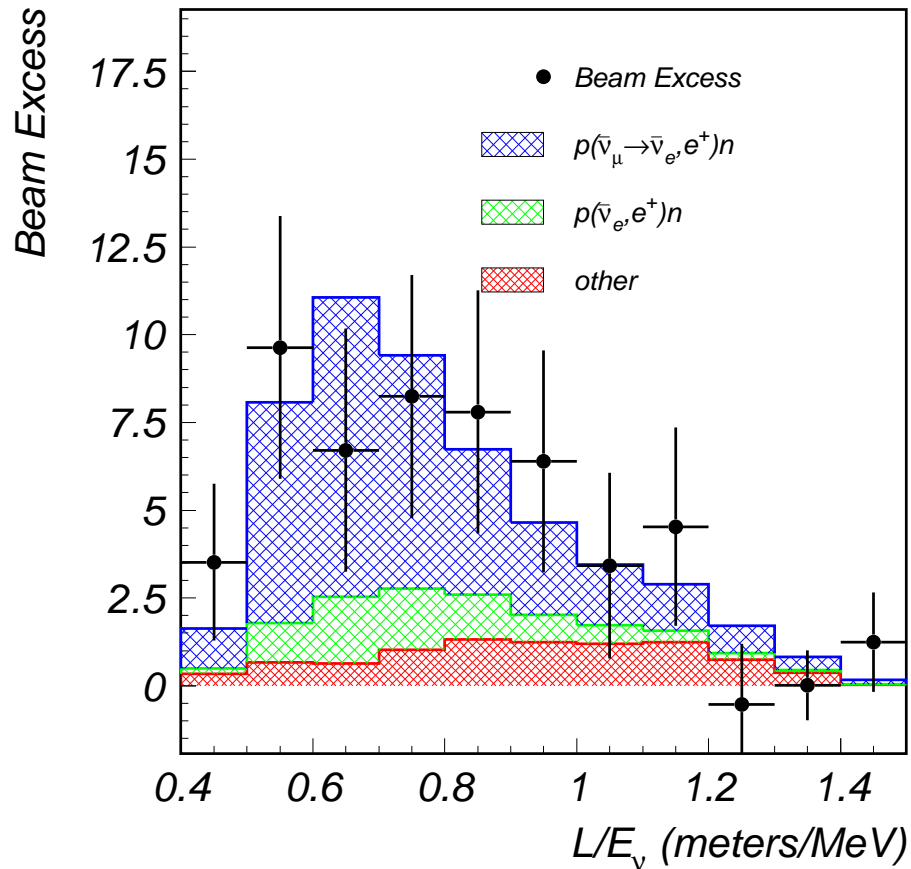$$

$$
m_1^2 < m_2^2
$$

$$
m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|
$$

$$
\tan^2 \theta_{12} \equiv \frac{|U_{e2}^2|}{|U_{e1}^2|}; \quad \tan^2 \theta_{23} \equiv \frac{|U_{\mu 3}^2|}{|U_{\tau 3}^2|};
$$

$$
U_{e3} \equiv \sin \theta_{13} e^{-i\delta}
$$

$\Delta m_{13}^2 > 0$ – Normal Mass Hierarchy

$\Delta m_{13}^2 < 0$ – Inverted Mass Hierarchy

The LSND Anomaly

If oscillations $\Rightarrow \Delta m^2 \sim 1$ eV^2;

strong evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

× does not fit into 3 ν picture;

× 2 + 2 scheme "ruled out" (solar, atm);

× 3 + 1 scheme "disfavored" (sbl searches);

× CPTV "ruled out" (KamLAND, atm);

× $\mu \rightarrow e\nu_e\bar{\nu}_e$ "disfavored" (KARMEN);

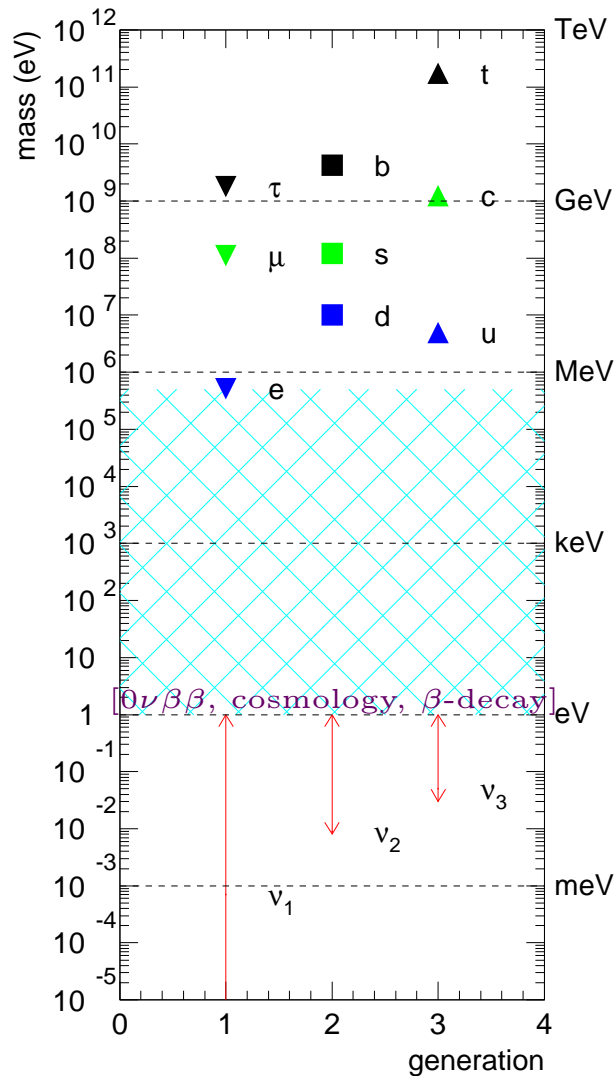○ 3 + 1 + 1 scheme works (finely tuned?);

○ something completely different;

$\Downarrow$

[this one gets my vote!]

What We Know We Don't Know

(from A. Smirnov, hep-ph/0311259)
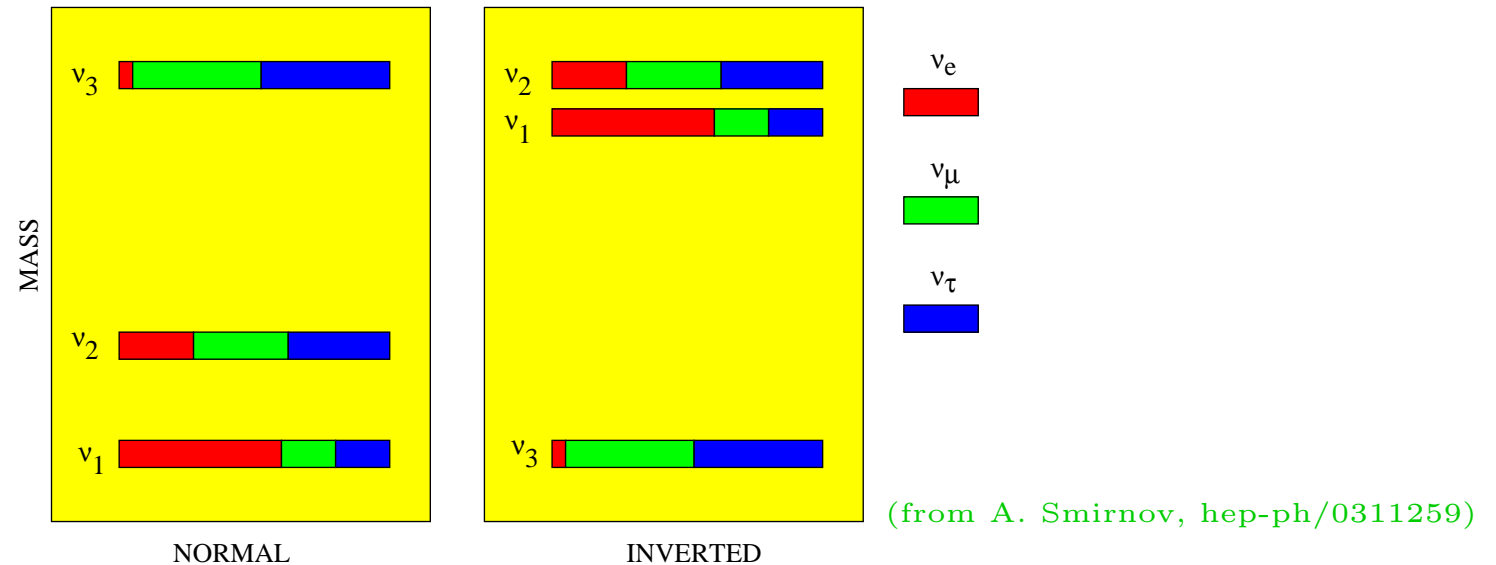
- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)

- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)

- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)

- What is the neutrino mass hierarchy? ($\Delta m_{13}^2 > 0$?)

2. Neutrino Masses Are Small

Neutrinos Have Mass

⇒ NEW PHYSICS

⇐ furthermore, neutrino masses are tiny!

We don't know why that is, but we have a "gut feeling" it means something important.

Are neutrinos fundamentally different?

Are neutrino masses generated by a distinct dynamical mechanism?

The νSM – "Default" Candidate

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\text{SM}} \supset -\lambda_{ij} \frac{L^i H L^j H}{2M} + \mathcal{O}\left(\frac{1}{M^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $M \gg 1$ TeV, it leads to only one observable consequence...

after EWSB $\mathcal{L}_{\nu\text{SM}} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = \lambda_{ij}\frac{v^2}{M}.$

- Neutrino masses are small: $M \gg v \rightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)

- Neutrinos are Majorana fermions – Lepton number is violated!

- νSM effective theory – not valid for energies above M

- What is M? First naive guess is that M is the Planck scale – does not work. Data require $M < 10^{15}$ GeV $\rightarrow$ GUT Scale!

Example – The Seesaw Mechanism

There are several ways to "UV-complete" this theory. The most elegant one is the see-saw mechanism [Yanagida (1979), Gell-Mann, Ramond, Slansky (1979), Glashow (1979), Mohapatra, Senjanovic (1980)]:

$$\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.,} \Rightarrow N^\alpha \text{ gauge singlet fermions,}$$
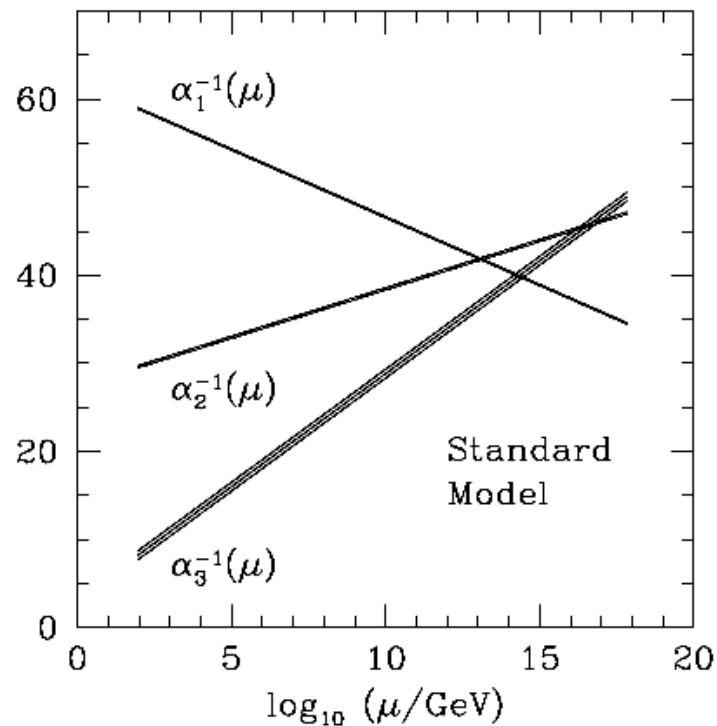
$y_{i\alpha}$ dimensionless Yukawa couplings, $M_N^{\alpha\beta}$ (very large) mass parameters.

For energies much smaller than M_N, we can integrate out the "right-handed" neutrinos N_α, and obtain the effective Lagrangian
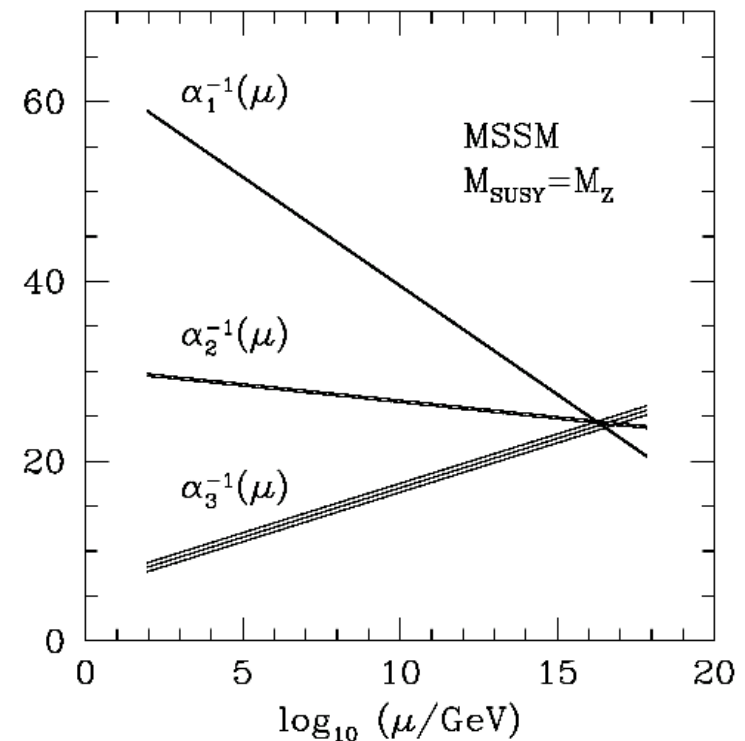
$$\mathcal{L} \supset \left(y^{\mathrm{t}} M_N^{-1} y\right)_{ij} L^i H L^j H + \mathcal{O}\left(\frac{1}{M_N^2}\right) + H.c.$$

Comparing with the previous Lagrangian $\Rightarrow \frac{\lambda}{2M} = \left(y^{\mathrm{t}} M_N^{-1} y\right)$

Other (Indirect) Evidence for New Physics Scale:

Evolution of Gauge Couplings

[from talk by K. Babu]

Standard Model

Supersymmetry

Right-handed neutrinos are "predicted" in SO(10) GUT Theories.

Matter particles unify into a **16** of SO(10):

$$\Psi = \begin{pmatrix} u_L \\ u_L \\ u_L \\ u_R \\ u_R \\ u_R \\ d_L \\ d_L \\ d_L \\ d_R \\ d_R \\ d_R \\ e_L \\ e_R \\ \nu_L \\ \boxed{N} \end{pmatrix}$$

Majorana Masses for N_α arise after SO(10) breaking:

$M_N \propto M_{\mathrm{GUT}}, \rightarrow$ prop constant model dependent

$e.g.$

$$M_N \simeq \frac{M_{\mathrm{GUT}}}{16\pi^2} \ (\text{"one-loop"} \ M_N)$$

$$M_N \simeq \frac{M_{\mathrm{GUT}}^2}{M_{\mathrm{Pl}}} \ (\text{"Planck suppressed"} \ M_N)$$

(and further suppression can be obtained from small couplings and/or flavor symmetries)

3. Understanding Fermionic Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

It means that leptonic mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$$[|(V_{MNS})_{e3}| < 0.2]$$

$$\boxed{\text{WHY?}}$$

They certainly look VERY different, but which one would you label as "strange"?

In the quark sector, the small mixing angles are interpreted, together with the hierarchical quark masses, as evidence for extra structure in the SM, i.e., there is some underlying dynamical principle (symmetry) capable of telling one quark flavor from another.

The same "must be true" in the leptonic sector. After all, charged lepton masses are also hierarchical (we don't know whether the same is true for the neutrinos yet...) and, if GUTs have anything to do with Nature, quarks and leptons may well be different low-energy manifestations of a more fundamental unified fermion.

Hence, there should also be a dynamical principle which naturally explains the form of the MNS matrix. (or should there?...)

First Prediction: $V_{CKM} \simeq V_{MNS}$

→ "driving force" before 1998 SK results, turned out to be completely wrong.

$\Delta m^2_{13} > 0$

"typical"

prediction

of all*

Type-I

GUT

models

inverted

hierarchy

requires*

"more

flavor

structure"

*Albright,hep-ph/0407155

[from reactor white paper]

The literature on this subject is very large. The most exciting driving force (my opinion) is the fact that one can make *bona fide* predictions:

$\Rightarrow U_{e3}$, CP-violation, mass-hierarchy unknown!

Unfortunately, theorists have done too good a job, and people have successfully predicted everything...

More data needed to "sort things out," which is why we are here!

Reference	$\sin\theta_{13}$	$\sin^2 2\theta_{13}$
SO(10)		
Goh, Mohapatra, Ng [40]	0.18	0.13
Orbifold SO(10)		
Asaka, Buchmüller, Covi [41]	0.1	0.04
SO(10) + flavor symmetry		
Babu, Pati, Wilczek [42]	$5.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-6}$
Blazek, Raby, Tobe [43]	0.05	0.01
Kitano, Mimura [44]	0.22	0.18
Albright, Barr [45]	0.014	$7.8 \cdot 10^{-4}$
Maekawa [46]	0.22	0.18
Ross, Velasco-Sevilla [47]	0.07	0.02
Chen, Mahanthappa [48]	0.15	0.09
Raby [49]	0.1	0.04
SO(10) + texture		
Buchmüller, Wyler [50]	0.1	0.04
Bando, Obara [51]	0.01 .. 0.06	$4 \cdot 10^{-4}$ .. 0.01
Flavor symmetries		
Grimus, Lavoura [52, 53]	0	0
Grimus, Lavoura [52]	0.3	0.3
Babu, Ma, Valle [54]	0.14	0.08
Kuchimanchi, Mohapatra [55]	0.08 .. 0.4	0.03 .. 0.5
Ohlsson, Seidl [56]	0.07 .. 0.14	0.02 .. 0.08
King, Ross [57]	0.2	0.15
Textures		
Honda, Kaneko, Tanimoto [58]	0.08 .. 0.20	0.03 .. 0.15
Lebed, Martin [59]	0.1	0.04
Bando, Kaneko, Obara, Tanimoto [60]	0.01 .. 0.05	$4 \cdot 10^{-4}$ .. 0.01
Ibarra, Ross [61]	0.2	0.15
3×2 see-saw		
Appelquist, Piai, Shrock [62, 63]	0.05	0.01
Frampton, Glashow, Yanagida [64]	0.1	0.04
Mei, Xing [65] (normal hierarchy)	0.07	0.02
(inverted hierarchy)	> 0.006	$> 1.6 \cdot 10^{-4}$
Anarchy		
de Gouvêa, Murayama [66]	> 0.1	> 0.04
Renormalization group enhancement		
Mohapatra, Parida, Rajasekaran [67]	0.08 .. 0.1	0.03 .. 0.04

Table 1: Incomplete selection of predictions for θ_{13}. The numbers should be considered as order of magnitude statements.

Qualitative descriptions of why V_{MNS} and V_{CKM} could turn out to be so different in a GUT theory [apologies to experts in the audience]:

- Large neutrino mixing "comes from M_N" – remember, while $m_f = yv$,
  $$m_\nu = y^{\mathrm{t}} M_N^{-1} y$$

- "SU(5) inspired" mixing: *left-handed* leptons and *right-handed* down-type quarks are in a **5** of SU(5), while everyone else is in a **10**. If the **5**'s are strongly mixed, we would only be able to see it in the leptonic sector, since one is always free to redefine right-handed fermions without physical consequences (because of left-handedness of weak interactions).
  [$\rightarrow$ interesting consequences in quark flavor physics if one adds SUSY]

- large mixing induced via renormalization group running

- . . .

Something Completely Different (?) –

maybe we are asking the wrong question! Notice that quark mixing is the one that fits the "strange" label → this is why we are convinced that there is some "hint" of more fundamental physics hidden in the CKM matrix!

Lepton mixing, on the other hand, seems quite "ordinary." Maybe the MNS matrix is what one should expect if there was no fundamental principle "hidden" behind neutrino mixing. → *Neutrino Mass Anarchy*

Anarchy is resistant against hierarchical charged lepton masses, GUT constraints. The relevant questions are 1-can we test whether the idea is plausible and 2-can we learn anything from it?   (yes, and yes!)

My only complaint is the fact that θ_{23} is maximal. But "when" should we start worrying about this? (to be discussed in the next-to-next slide)

Lower Bound for $|U_{e3}|^2$

[AdG, Murayama, PLB573, 94 (2003)]
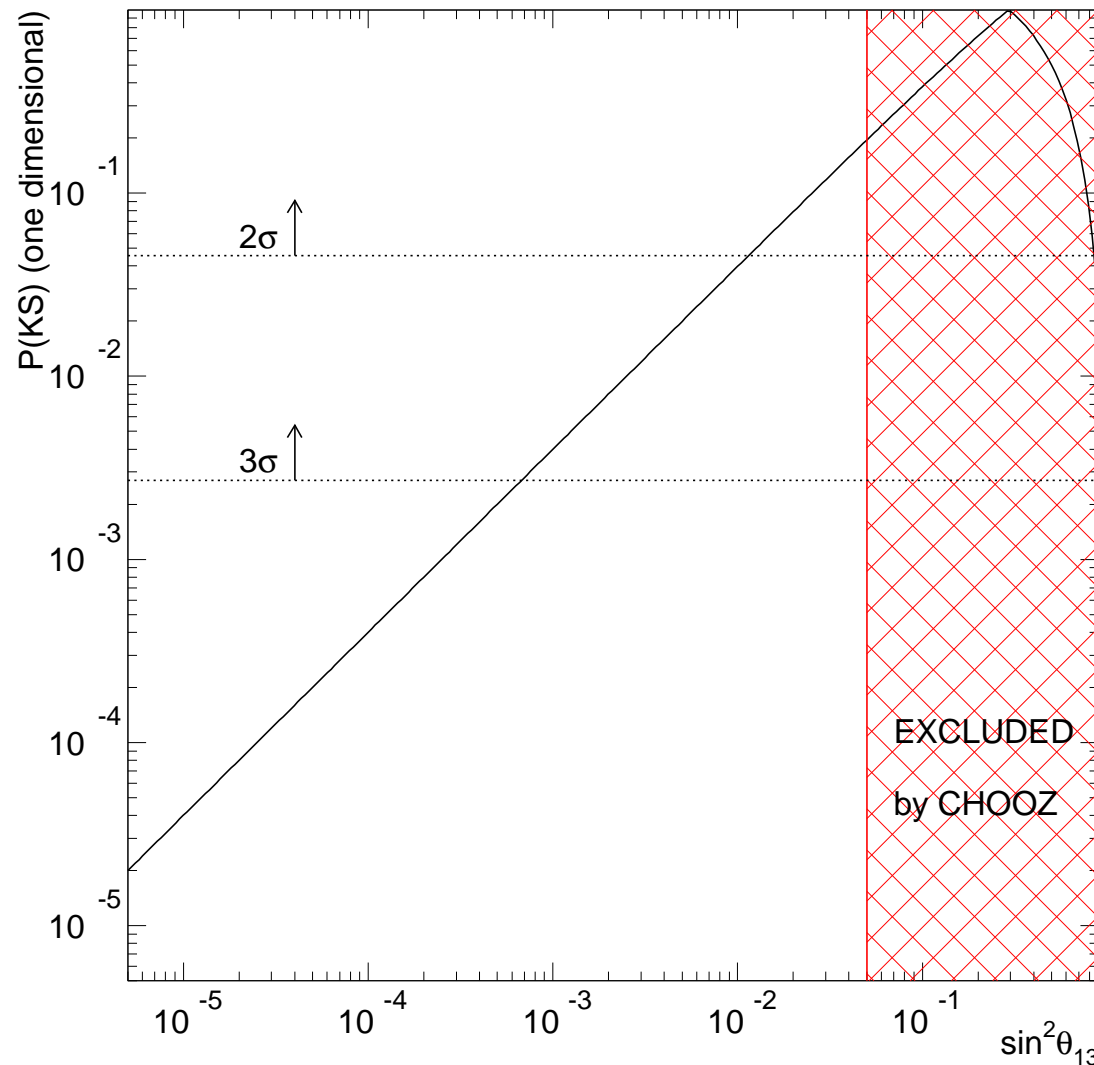
according to the anarchical hypothesis, the probability density distribution for θ_{13} is given by $P(\theta_{13}) \propto \cos^4 \theta_{13}$

[Haba, Murayama, PRD63,053010 (2001)]

The probability that $|U_{e3}|^2$ is larger than 0.01 is around 95%, and if $|U_{e3}|^2$ turns out to be smaller, the anarchical hypothesis is "ruled out"!

(Prob. distribution for CP-phase: $P(\delta) \propto 1$)

generic predictions

for subleading

parameters. Note

correlations between

$|U_{e3}|$ and $\cos 2\theta_{23}$,

plus dependency on

mass-hierarchy.

Case	Texture	Hierarchy	$|U_{e3}|$	$|\cos 2\theta_{23}|$ (n.s.)	$|\cos 2\theta_{23}|$	Solar Angle
A	$\frac{\sqrt{\Delta m_{13}^2}}{2}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix}$	Normal	$\sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}}$	O(1)	$\sqrt{\frac{\Delta m_{12}^2}{\Delta m_{13}^2}}$	O(1)
B	$\sqrt{\Delta m_{13}^2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Inverted	$\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$	–	$\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$	O(1)
C	$\frac{\sqrt{\Delta m_{13}^2}}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$	Inverted	$\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$	O(1)	$\frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$	$|\cos 2\theta_{12}| \sim \frac{\Delta m_{12}^2}{|\Delta m_{13}^2|}$
Anarchy	$\sqrt{\Delta m_{13}^2}\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$	Normal[a]	> 0.1	O(1)	–	O(1)

[a]One may argue that the anarchical texture prefers but does not require a normal mass hierarchy.

"Textures" are another way to parametrize neutrino mixing and to try and understand salient features: $|U_{e3}| \ll 1$, $\cos 2\theta_{23} \ll 1$, $\Delta m_{12}^2 \ll \Delta m_{13}^2$, etc. Usually "quark independent."

4. Comments on Baryogenesis via Leptogenesis

One of the most basic questions we are allowed to ask (with any real hope of getting an answer) is whether the observed baryon asymmetry of the Universe can be obtained from a baryon–antibaryon symmetric initial condition plus well understood dynamics. [Baryogenesis]

This isn't just for aesthetic reasons. If the early Universe undergoes a period of inflation, baryogenesis is required, as inflation would wipe out any pre-existing baryon asymmetry.

It turns out that massive neutrinos can help solve this puzzle!

In the old SM, (electroweak) baryogenesis does not work – not enough CP-invariance violation, Higgs boson too light.

Neutrinos help by providing all the necessary ingredients for successful baryogenesis via leptogenesis.

- Violation of lepton number, which later on is transformed into baryon number by nonperturbative, finite temperature electroweak effects (in one version of the νSM, lepton number is broken at a high energy scale M).

- Violation of C-invariance and CP-invariance (weak interactions, plus new CP-odd phases).

- Deviation from thermal equilibrium (depending on the strength of the relevant interactions).

E.g. – thermal, seesaw leptogenesis, $\boxed{\mathcal{L} \supset -y_{i\alpha}L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2}N_\alpha N_\beta + H.c.}$
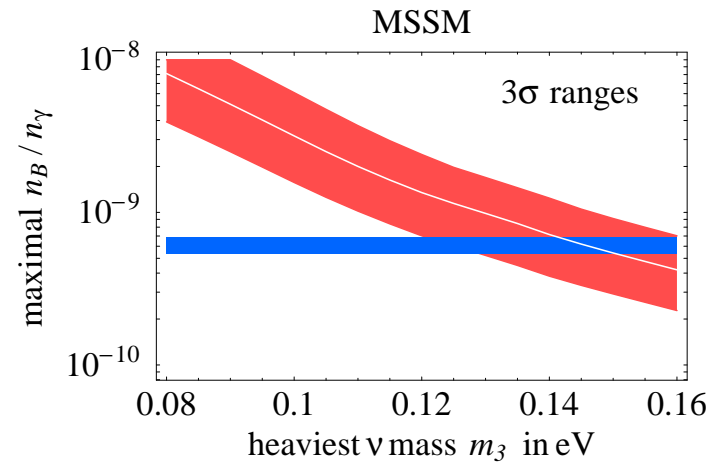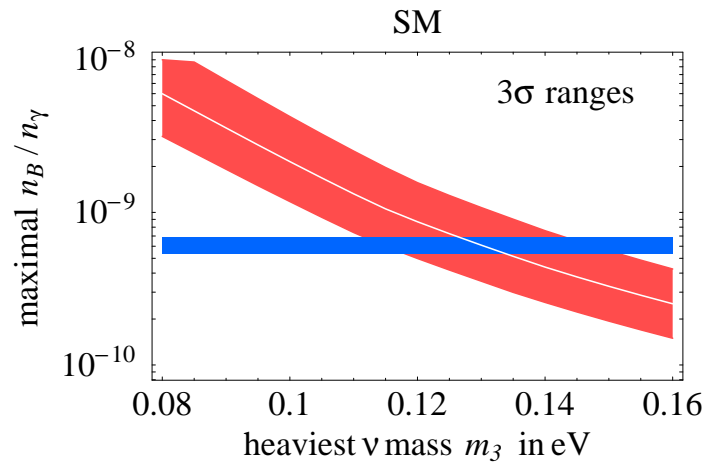
[Fukugita, Yanagida]
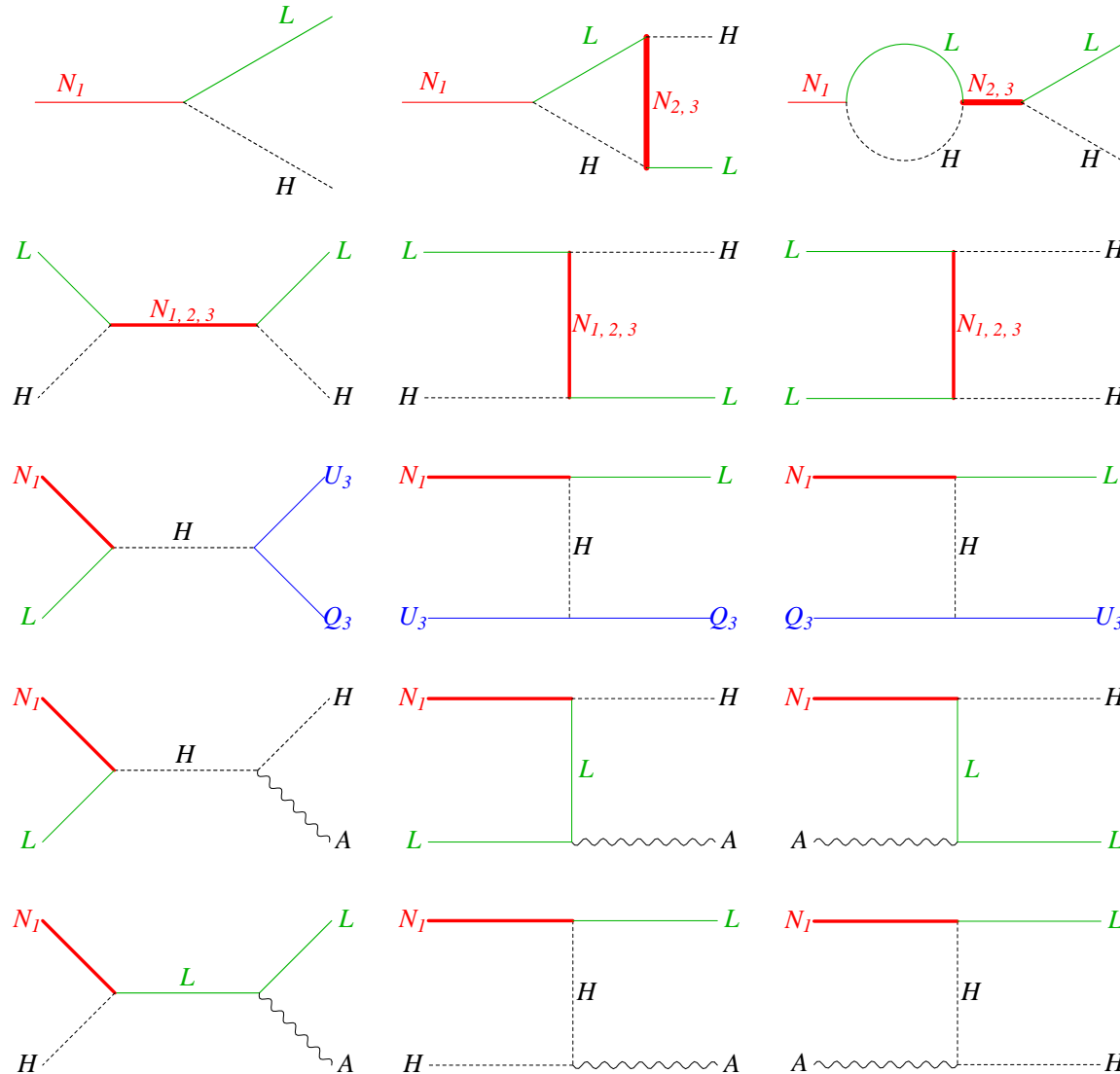
- L-violating processes

- $y \Rightarrow$ CP-violation

- deviation from thermal eq. constrains combinations of M_N and y.

- need to yield correct m_ν

not trivial!

[G. Giudice *et al*, hep-ph/0310123]

E.g. – thermal, seesaw leptogenesis, $\boxed{\mathcal{L} \supset -y_{i\alpha} L^i H N^\alpha - \frac{M_N^{\alpha\beta}}{2} N_\alpha N_\beta + H.c.}$

[G. Giudice *et al*, hep-ph/0310123]

It did not have to work – but it does

MSSM picture does not quite work – gravitino problem

(there are ways around it, of course...)

Relationship to Low Energy Observables?

In general . . . no. This is very easy to understand. The baryon asymmetry depends on the (high energy) physics responsible for lepton-number violation. Neutrino masses are one of many consequences of this physics, albeit the only observable ones at the "low-energy" experiments we are able to perform.

see-saw: y, M_N have more physical parameters than $m_\nu = y^{\mathrm{t}} M_N^{-1} y$.

There could be a relationship, but it requires that we know more about the high energy Lagrangian (model depent). The day will come when we have enough evidence to refute leptogenesis (or strongly suspect that it is correct) - but more information is really necessary (charged-lepton flavor violation, collider data on EWSB, lepton-number violation, precise oscillation parameter measurements,etc).

$\Bigg($ There are other "kinds" of leptogenesis, about which I'll say nothing

- Nonthermal leptogenesis

- Type-II see-saw leptogenesis

- Dirac leptogenesis   Lindner *et al*; Murayama and Pierce

- Soft leptogenesis (Theory Talk Tomorrow)   Grossman *et al*; Giudice *et al*.

- ...

$\Bigg)$

5. Concluding Remarks

- We need to figure out the physics behind neutrino masses. Very ill-defined at this point!

- Precise determination of oscillation parameters will help set theorists on the correct path. Whether $|U_{e3}|^2$ is larger than 0.01 seems to be a particularly useful issue to address (anarchy?, new symmetry?, what is the best next-generation set-up for neutrino osc. experiments?), together with establishing the mass hiearchy (and is $\cos 2\theta_{23} < 0.1$?).

- Remember that neutrino masses may be our only handle on extremely high energy scales (modulo, say, proton decay)!

- Finally, let us not forget about the LSND anomaly (at least, not for another year or so?)! Life could be (will be?) much more exciting!